GOATS 2005
Integrated, Adaptive Autonomous Acoustic Sensing Systems

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LONG-TERM GOALS

To develop net-centric, autonomous underwater vehicle sensing concepts for littoral MCM and ASW, exploring collaborative and environmentally adaptive, bi- and multi-static sonar configurations for concurrent detection, classification and localization of proud and buried targets.

OBJECTIVES

The objective of the continuing GOATS interdisciplinary research program is to develop, implement and demonstrate real-time, onboard integrated acoustic sensing, signal processing and platform control algorithms for adaptive, collaborative, multiplatform REA, MCM, and ASW in unknown and unmapped littoral environments with uncertain navigation and communication infrastructure.

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14. ABSTRACT
To develop net-centric, autonomous underwater vehicle sensing concepts for littoral MCM and ASW, exploring collaborative and environmentally adaptive, bi- and multi-static sonar configurations for concurrent detection, classification and localization of proud and buried targets.

15. SUBJECT TERMS

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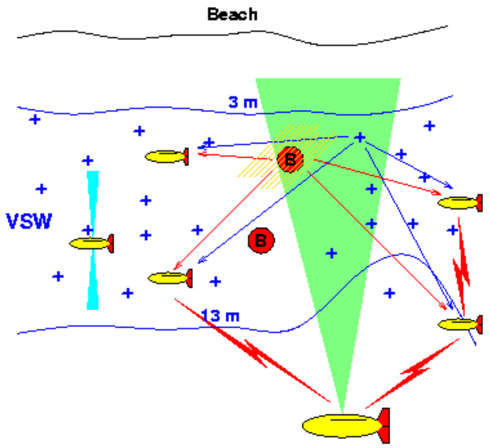

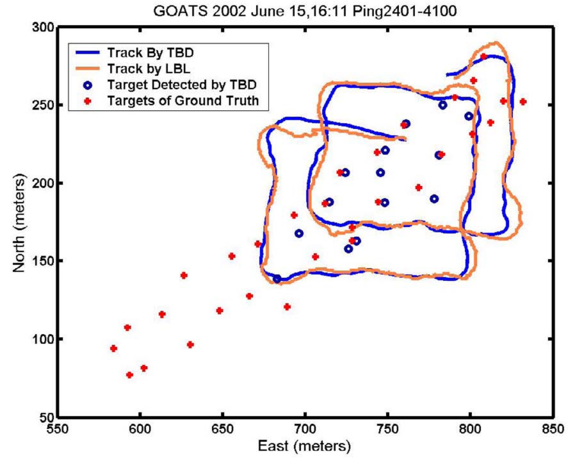

APPROACH

The GOATS (Generic Ocean Array Technology Sonar) research program is a highly interdisciplinary effort, involving experiments, theory and model development in advanced acoustics, signal processing, and robotics. The center-piece of the research effort has been a series of Joint Research Projects (JRP) with SACLANTCEN. The joint effort was initiated with the GOATS' 98 pilot experiment [1] and continued with the GOATS’ 2000 and BP02/MASAI02 experiments. Currently the collaboration is being continued under two NURC JRPs – one on hybrid target scattering modeling, and one on Focused Acoustic Fields (FAF), which constituted part of the joint experiments in 2004-05. In addition to the field experiments involving significant resources provided by NURC, GOATS uses modeling and simulation to explore the potential of autonomous underwater vehicle networks as platforms for new sonar concepts exploring the full 3-D acoustic environment of shallow water (SW) and very shallow water (VSW).

The fundamental approach of GOATS is the development of the concept of a network of AUVs as an array of *Virtual Sensors*, based on fully integrated sensing, modeling and control, reducing the inter-platform communication requirements to be consistent with the low bit-rate reality of shallow water acoustic communication. Thus, for example the past GOATS effort has demonstrated that platform motion information can be used for clutter control by providing geometric constrains to on-board detection algorithms, reducing the communication requirements to location, POD, and classification information. Conversely, on-board sensor fusion and processing can be fed back to the vehicle control system for autonomous, adaptive sampling – again with the potential for significantly enhanced POD/PFA performance.

The sonar sensing in GOATS uses the bi-static and multi-static Synthetic Aperture created by the network, in combination with low frequency (1-10 kHz) wide-beam insonification to provide coverage, bottom penetration and location resolution for concurrent detection, localization and classification of proud and buried targets in SW and VSW. The signal processing effort in GOATS is therefore centered around generalizing SAS processing to bi-static and multi-static configurations, including bi-static generalizations of autofocusing and track-before-detect (TBD) algorithms. Another issue concerns the stability and coherence of surface and seabed multiples and their potential use in advanced low-frequency SAS concepts.

GOATS involves a significant effort addressing the fundamental robotics issues associated with the collaborative operation of multiple autonomous underwater vehicles in shallow water, including navigation, inter-platform acoustic communication, and adaptive, cooperative behavior. Specifically, the current effort explores the development of Concurrent Mapping and Localization (CML) algorithms for networks of AUVs and the implementation of efficient inter-vehicle acoustic communication protocols enabling the cooperative behavior which is crucial to the implementation of the GOATS concept.

The development of the GOATS concept is based heavily on simulation, incorporating and integrating high-fidelity acoustic modeling, platform dynamics and network communication and control. In regard to the environmental acoustic modeling, MIT continues to develop the OASES-3d modeling framework for target scattering and reverberation in shallow ocean waveguides. The most recent development has provided a unique target scattering model incorporating multiple scattering between targets and the seabed. Using a generalized virtual source approach, the scattering from arbitrarily shaped elastic targets, partially or completely buried in the seabed can be modeled, two orders of magnitude faster than the alternative use of Finite Elements. Most recently the new target scattering models have been integrated with a network simulation capabilty to constitute a complete MCM simulation framework, MIT-MCM, described below.

WORK COMPLETED

MIT-MCM Simulation Framework

In support of GOATS and the related SWAMSI effort, a comprehensive simulation package, with the working title MIT-MCM, has been developed to provide coherent acoustic pressure time series for shallow water operations involving multiple sources, receivers and targets within a confined area [2]. MIT-MCM has the capability to dynamically plan the vehicle path in "real-time" mode, provide for reflections from the seabed and sea surface, and the capability to run adaptive missions with multiple sources, receivers and targets. The MIT-MCM package is designed to resemble the experimental process, and to include as much of the relevant physics as possible. A replay mode is included so that simulated or at-sea experiments can be reproduced in whole or in part in order to test different processing algorithms or physical processes. The represented physical phenomena include reverberation realizations, multipath, propagation modeling and target scattering. The target scattering is modeled using analytical models for simple targets and the Virtual Source approach [3] for more complex targets. The seabed reverberation model is based on the work by Ricks [4], with the unique feature of providing ping-to-ping consistent realizations. This feature is crucial to simulation of vehicle self-navigation through SAS auto-focusing.

3D Coupled Mode Modeling

To enable high-fidelity modeling of 3D propagation in shallow water with complex bathymetry, MIT has developed a new coupled mode framework, based on the NURC CSNAP legacy model [5]. For three dimensional problems, the new model can be applied to solve problems involving oblique interaction, including back-scatter, with linear seabed features such as ridges, and propagation around conical seamounts. The model has been completed for linear features, while the solution for the cylindrical features is ongoing, and currently limited to propagation around a cylindrical island.

Cooperative, Moving Long Baseline Navigation

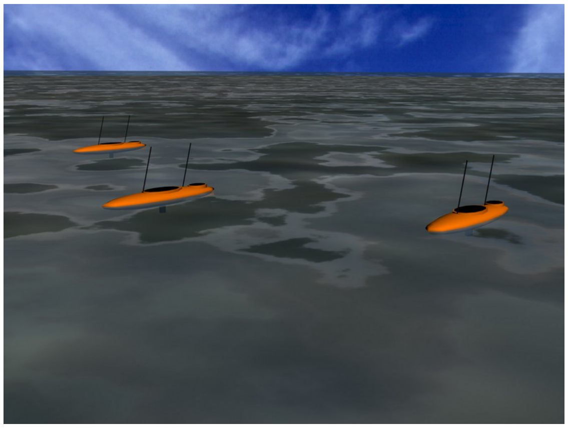

Figure 1: MLBL using ASCs only

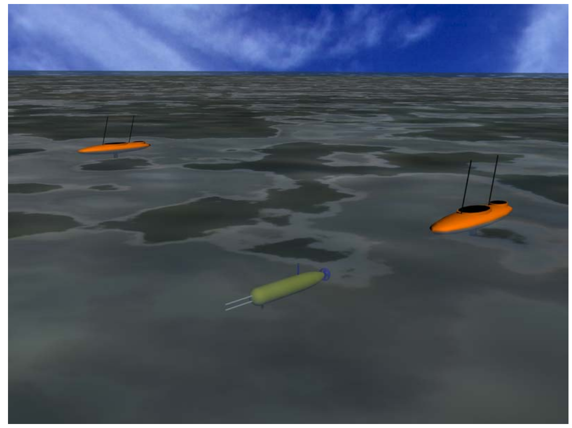

Figure 2: MLBL using a mix of AUVs and ASCs

The concept of collaborative, moving long baseline navigation (MLBL) is being explored by MIT, in part under GOATS. MIT has demonstrated the feasibility of cooperative, moving long baseline navigation using our fleet of AUVs and Autonomous Surface Crafts (ASCs), through a series of experiments on the Charles River and most recently as part of the FAF'05 experiment in Italy. The river experiments replace all AUVs by ASCs, Fig. 1, while in FAF'05 a submerged AUV was combined with two ASC as baseline, 2. In addition to the logistic simplicity, the use of ASCs allow to visually check the experiment while it is running and GPS provides ground-truth data.

RESULTS

MIT-MCM Simulation Framework

SAS Imagery The fidelity of the time series generated by the MIT-MCM framework is illustrated through the formation of SAS imagery in Fig. 3 . A target field consisting of 3 targets is simultaneously imaged by 2 AUVs passing on opposite sides of the target field, including buried, proud targets of different different shapes..

Adaptive Missions Adaptive missions are handled in MIT-MCM through Matlab or shell scripting. Once the output files are written, the data can be processed with whatever processing code is under test, and the next desired position computed. The input files for the sources and receivers can then be modified, and the simulation can then be executed for the following ping appended to the current mission. Some examples of simulated sonar-adaptive missions, are shown in Fig. 4.

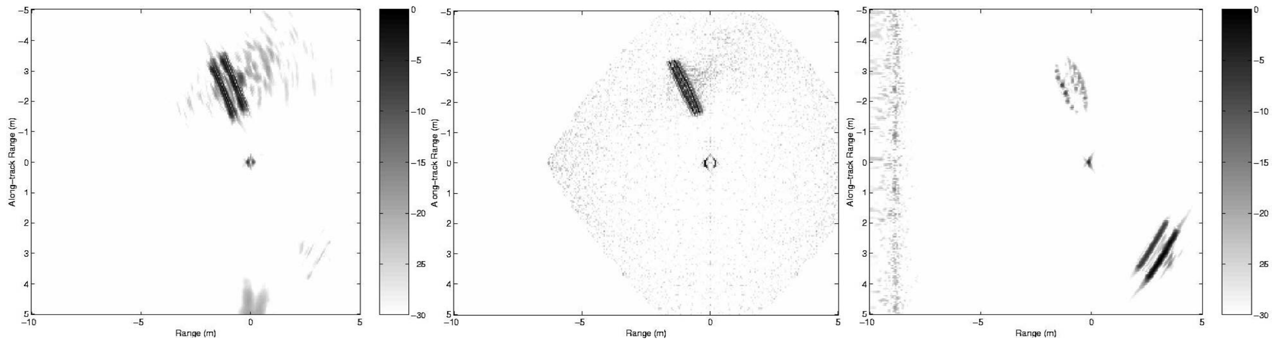

Figure 3. SAS imagery generated from MIT-MCM simulated output. On the left a 5 kHz source insonifies a target field with 2 cylinders and a sphere. The cylinder located at (3,3) is buried, and just detectable at the bottom of the image. The center plot is the same image at 30 kHz, and the buried target is not detected. On the right, the top target is buried spheroid, and the bottom cylinder is proud.

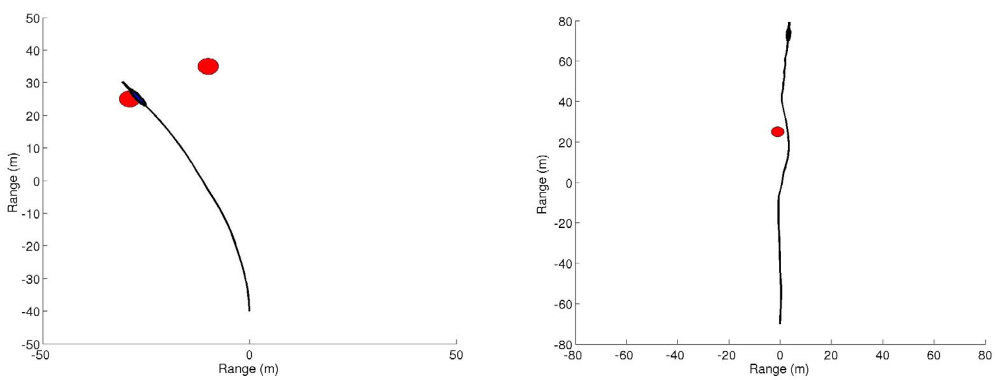

Figure 4. Sonar-adaptive mission simulations. On the left, the vehicle "hunts" an object. On the right, the vehicle avoids an object.

3D Coupled Mode Modeling

Three dimensional scattering from and diffraction around a cylinder-shaped island in a 200 m deep shallow water environment is being applied as a benchmark problem for the new 3D mode coupling framework. The geometry is shown in Fig. 5, while the computed two-way transmission loss at a depth of 67 m is shown in Fig. 6.

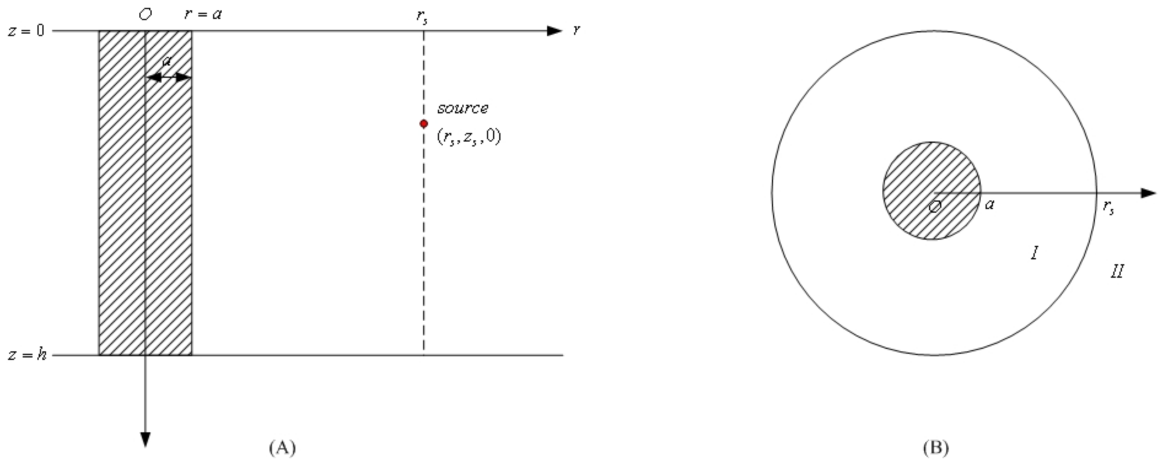

Figure 5 Geometry of cylinder island problem

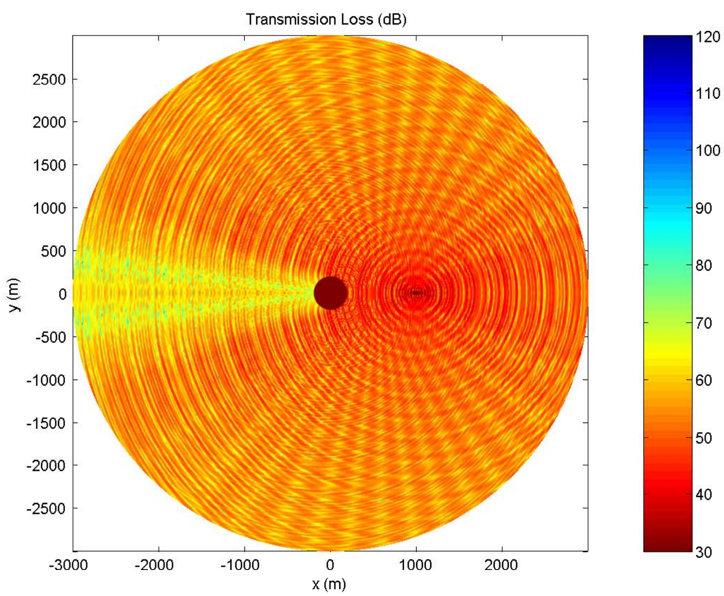

Figure 6 Transmission loss in xy-plane at depth z=h/3

Cooperative, Moving Long Baseline Navigation

The Charles River MLBL experiments were performed with 4 ASCs (kayaks) equipped with WHOI micromodems and GPS. By providing a GPS-PPS signal to all modems one-way ranges were obtained with each data transmission. Fig. 7 shows the trajectories of the ASCs during the test: two ASCs were attached to the pier while a third one ran a preprogrammed box which took it between 100m and 700m away from the other ASCs. Fig. 8 shows the distance between a traveling ASC and one that is attached to the pier. The black circles represent distances as estimated by the acoustic modem, the blue line show the “true” distance as obtained by the GPS. Fig. 8 shows that the acoustic range measurements

are very accurate and make the micromodem a useful tool for integrated navigation and communication.

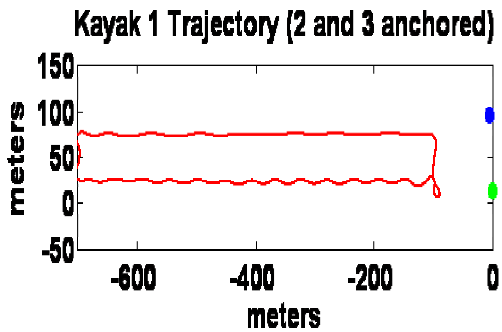

Figure 7: Trajectories of ASC during modem test

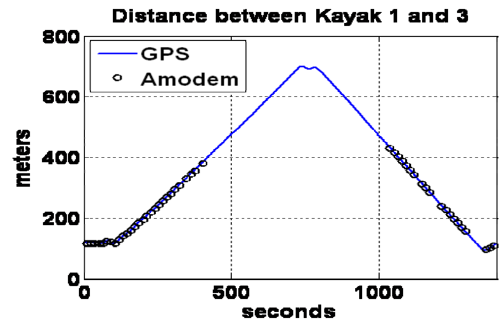

Figure 8: Intra-ASC range based on GPS vs. acoustic range

As a second step we ran three ASCs in a triangle formation. A lead ASC was set on a preprogrammed track and continuously broadcasted its GPS position. Two following ASCs then used these broadcasts to position themselves to form a triangle formation. While the formation was running the two following ASCs transmitted their GPS positions over the acoustic modem. The acoustic messages received on the lead ASC were the used to compute the lead ASC's position in post processing. Fig. 9 shows the GPS based tracks of all three ASCs (red, green, blue) and the lead ASC's track computed based on the received modem transmissions (black). While the computed track shows some outliers, the results show that it is possible to obtain position information with outside fixes. The next steps will built on the used algorithm while improving the outlier rejection.

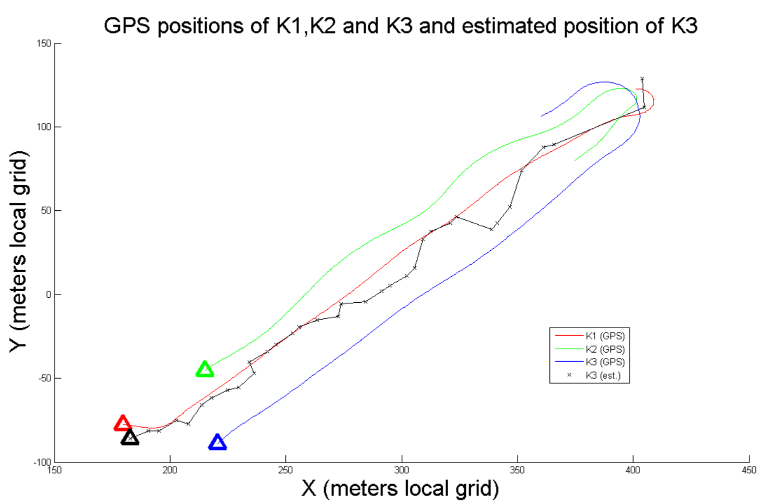

Figure 9: GPS positions of all three ASCs (red, green, blue) and estimated position of lead ASC (black)

IMPACT/APPLICATIONS

The long-term impact of this effort is the development of new sonar concepts for VSW MCM, which take optimum advantage of the mobility, autonomy and adaptiveness of an autonomous, cooperating vehicle network. For example, bi- and multi-static, low-frequency sonar configurations are being explored for completely or partially proud or buried mines in shallow water, with the traditional high-resolution acoustic imaging being replaced by a 3-D acoustic field characterization as a combined detection and classification paradigm, exploring spatial and temporal characteristics which uniquely define the target and the reverberation environment.

Navigation is a crucial component of a net-centric autonomous sensing system, in particular when deployed in denied, unknown environments. The successful development of the autonomous, moving baseline navigation concept explored here will have large impact on the design of operational systems for persistent littoral surveillance and MCM.

TRANSITIONS

The progress made in autonomous, multi-AUV, net-centric control, navigation, communication, and collaborative sensing is being transitioned into the ASAP-MURI and the new Undersea Persistent Surveillance (UPS) PLUSNet efforts, both of which have which MIT as partners, with field demonstrations of autonomous adaptive sensing and control in Monterey Bay in FY06. PI Schmidt is Co-lead PI on PLUSNet.

Particular emphasis in FY05 was aimed at transitioning the active MCM sonar concepts developed and demonstrated under GOATS, to the autonomous, littoral ASW problem, currently being addressed in the ONR Undersea Persistant Surveillance (UPS) program. The FAF'05 experiment July 11-29, 2005, carried out jointly with NURC, was aimed at adapting the integrated sensing, modeling and control paradigm to the passive ASW DCL problem. The DCLN sonar developed and demonstrated under GOATS was modified to continuously stream data from the nose arrays on the MIT BF21 vehicles, and real-time DCL algorithms and adaptive vehicle control, developed for the MCM problems were modified and successfully demonstrated for real-time, autonomous detection,localization and tracking of a moving source.

The results of the multi-vehicle navigation, communication and cooperative behavior is being transitioned into the Autonomous Operations Future Naval Capabilities (AOFNC) project *Demonstratio of Undersea, Autonomous Operation Capabilities and related Technology Development.* John Leonard is the MIT PI of this joint project with Bluefin Robotics and the Naval Undersea Warfare Center (NUWC).

The OASES and CSNAP environmental acoustic modeling codes are used extensively in this work and continue to be maintained, expanded and made available to the community. It is continuously being exported or downloaded from the OASES web site, and used extensively by the community as a reference model for ocean seismo acoustics in general.

(http://acoustics.mit.edu/arctic0/henrik/www/oases.html) Among the new transitions to applied Navy programs, the OASES and CSNAP framework is being used extensively by several contractors such including Lockheed-Martin, BBN, Northrop-Grumman, and SAIC., and Navy laboratories, including NUWC, NURC, CSS, and NRL.

RELATED PROJECTS

This effort has constituted part of the US component of the GOATS`2000 Joint Research Project (JRP) with the SACLANT Undersea Research Centre, and is currently collaborating with NURC under the Hybrid Target Modeling and Focused Acoustic Field (FAF) Joint Research Projects (JRP). The MIT GOATS effort has been funded jointly by ONR codes 321OA (Livingston), 321OE (Swean,Curtin), and 321TS (Johnson/Loeffler/Commander).

The GOATS effort is strongly related to the ONR Autonomous Ocean Sampling Network (AOSN) initiative completed in FY00. Thus the GOATS'98 experimental effort was funded in part by the AOSN MURI, (PI: J. Bellingham). In terms of the fundamental seabed penetration physics there are strong relations to the now completed High-Frequency Bottom Penetration DRI (PI: E. Thorsos) and the current SAX initiative. This effort also builds on acoustic modeling efforts initiated under the Sea-Ice Mechanics Initiative (SIMI), and continued under funding from ONR code 321OA (Livingston).

GOATS is also strongly related to the new Shallow Water Autonomous Mine Sensing Initiative (SWAMSI), initiated in FY04, and of which MIT is a partner.

The OASES modeling framework being maintained and upgraded under this award has been used intensively as part of the MIT AREA (Adaptive Rapid Environmental Assesment) component of the now completed ONR "Capturing Uncertainty" DRI, aimed at mitigating the effect of sonar performance uncertainty associated with environmental uncertainty by adaptively deploying environmental assesment resources. The cooperative AUV behavior progress together with the AREA concept is being currently transitioned into the ASAP MURI and the Undersea Persistent Surveillance (UPS) program, with an experimental demonstration in Monterrey Bay in FY06.

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HONORS/AWARDS/PRIZES

Prof. Henrik Schmidt has been awarded the *Pioneers of Underwater Acoustics Medal* of the Acoustical Society of America, to be presented at the 150th Meeting of the ASA, Oct. 17-21, 2005 in Minneapolis, MN.

Winner of conference best paper award at *Second ACM Conference on Embedded Networked Sensor Systems (SenSys'04).* Baltimore, MD. November 3-5, 2004. (D. Moore, J. Leonard, D. Rus, S. Teller. Robust distributed network localization with noisy range measurements.)